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Left ventricular shape-based contractility index

Liang Zhong[a], Dhanjoo N. Ghista[b,*], Eddie Y.K. Ng[a], Soo T. Lim[c], Terrance S.J. Chua[c], Chuen N. Lee[d]

[a]*School of Mechanical and Aerospace Engineering, College of Engineering, Nanyang Technological University, Singapore 639798, Singapore*
[b]*School of Chemical and BioMedical Engineering, Division of Bioengineering, College of Engineering, Nanyang Technological University, 50, Nanyang Avenue, Singapore 639798, Singapore*
[c]*Department of Cardiology, National Heart Centre, SingHealth, Mistri Wing, 3rd Hospital Ave., Singapore 168752, Singapore*
[d]*Department of Cardiac, Thoracic and Vascular Surgery, National University Hospital, Level 2, Linkway, Main and Kent Ridge Wing, 5 Lower Keng Ridge Road, Singapore 119074, Singapore*

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Abstract

This study develops contractility indices in terms of the left ventricular (LV) ellipsoidal geometrical shape-factor. The contractility index (CONT1) is given by the maximum value $\mathrm{d}\sigma^*/\mathrm{d}t$ wherein $\sigma^* = \sigma/P$, σ is the wall stress, and σ^* is expressed in terms of the shape factor S (the ratio of the minor axis and major axis, B/A, of the instantaneous LV ellipsoidal model). Another contractility index (CONT2) is also developed based on how far apart the in vivo S at the start of ejection is from its optimized value, $\mathrm{CONT2} = (S_{se} - S_{se}^{op})/S_{se}^{op}$, where S_{se} refers to the value of S at the start of ejection, S_{se}^{op} is the derived optimal value of S_{se} for which σ^* is maximum. The values of $S(=B/A)$ were calculated from cineventriculographically monitored LV volume, myocardial volume and wall-thickness. Then both the contractility indices were evaluated in normal subjects, as well as in patients with mild heart failure and in patients with severe heart failure. The normal values of CONT1 and CONT2 are $8.75 \pm 2.30\,\mathrm{s}^{-1}$ and 0.09 ± 0.07, respectively. CONT1 decreased in patients with mild and severe heart failures to 5.78 ± 1.30 and 3.90 ± 1.30, respectively. CONT2 increased in patients with mild and severe heart failures to 0.11 ± 0.09 and 0.23 ± 0.12, respectively. This implies that a non-optimal and less ellipsoidal shape is associated with decreased contractility (and poor systolic function) of the LV. CONT1 and CONT2 are useful as non-invasively determinable quantitative indices of LV contractility, to distinguish between normal and pathologic LVs.

Keywords: Left ventricle; Ellipsoidal model; Non-invasive; Contractility; Shape factor; Wall stress

1. Introduction

Over the past decades, several indices for estimating the left ventricular (LV) contractile state have been proposed, based on either empirical evidence or theoretical considerations. A great deal of effort has been made to assess their specificity and prediction capability (Mason et al., 1971; Peterson et al., 1974; Lambert et al, 1983; Kass et al., 1987; Kass and Beyer, 1993). Most studies have indicated the peak of the first time derivative of the ventricular pressure $\mathrm{d}P/\mathrm{d}t_{max}$ to be the most sensitive cardiac index of inotropic changes (Kass et al., 1987). The maximum value of $\mathrm{d}P/\mathrm{d}t$ is reached soon after aortic valve opening, after the myocardial fibers have started to shorten and expend part of their energy in providing both pressure and kinetic energy to the ejection blood. However, the intraventricular LV pressure is obtainable only by cardiac catheterization. To avoid the risk, inconvenience of catheterization, it would be advantageous to develop LV contractility indices by non-invasive methods, such as in terms of ejected blood acceleration expressed as the peak of the time derivation of the aortic flow rate (*f*),

*Corresponding author. Tel.: +65 6790 4441; fax: +65 6791 1859.
E-mail address: mdnghista@ntu.edu.sg (D.N. Ghista).

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Nomenclature

A	major axis of ellipsoidal model
B	minor axis of ellipsoidal model
V	left ventricular volume
MV	left ventricular myocardial volume
h	wall thickness of ellipsoidal model
S	shape factor ($=B/A$)
S_{se}	shape factor at start-of-ejection
S_{se}^{op}	optimal shape factor at start-of-ejection
P	left ventricular chamber pressure
σ	wall stress
σ^*	normalized wall stress (σ/P)
f_b	truncation factor
V^*	ratio of myocardial volume and volume ($=\text{MV}/V$)
V(se)	volume at start-of-ejection
V(ee)	volume at end-of-ejection
CONT1	left ventricular new contractility index ($=\lvert d\sigma^*/dt\rvert_{max}$)
CONT2	left ventricular new contractility index ($=(S_{se}-S_{se}^{op})/S_{se}^{op}$)
dP/dt_{max}	left ventricular traditional contractility index
EF	ejection fraction ($=$ SV/EDV)
SV	stroke volume
EDV	end-diastolic volume of the left ventricle
se	start-of-ejection
ee	end-of-ejection
GWS	generated wall-stress
LVEM	left ventricular ellipsoidal model
SBCI	shape-based contractility index

df/dt_{max} (Bettett et al., 1984; Lazarus et al., 1988; Redaelli and Montevecchi, 1998) obtained from Doppler ultrasound.

To the best of knowledge, very few studies have been dedicated to the influence of the LV shape factor on its contractility. It has been observed that the shape of the LV is of clinical relevance for prognosis of heart patients (Tischler et al., 1993; Devereus, 1995; Krumholz et al., 1995; Juznic et al., 1998; Knap et al., 2002). In this regard, some investigators have associated a more spherically shaped and less-ellipsoidal shaped LV with the failing heart (Lee et al., 1993). Invasive animal experiments have indicated that the shape of the LV is somewhat like a prolate ellipsoid (De Anda et al., 1995). From cineventriculography, the two-dimensional shape of the LV can be obtained, and therefrom the ellipsoidal shape of LV. This information has been applied, herein, to develop a left-ventricular ellipsoidal geometry model and LV ellipsoidal-model wall stress. Now, a LV contractility index (CONT1) is defined to represent the capacity of the LV to develop necessary and sufficient intra-myocardial stress to provide necessary and sufficient pressure and kinetic energy to the ejected blood. Hence, it could gauge LV contractile capability in terms of the maximum value of developed intra-myocardial stress, or $(d\sigma/dt)_{max}$. Thus CONT1 can help provide more insight into the LV shape-based contractile stress for its ejection function.

This study is based on the premise that LV contractility index is a measure of the capacity of the LV myocardial sarcomere to contract and develop wall-stress that will adequately raise intra-LV pressure to eject the blood. Now since the LV wall stress depends on its shape, hence the LV contractile capacity also depends on the LV shape. This is the rationale behind the LV shape-based contractility index (SBCI). Based on clinical observations, a healthy LV shape factor is more akin to the optimal-ellipsoidal shape factor, but transforms into a more spherical shape in a poorly contracting LV as well as in LV failure. Hence, the LV SBCI expressed as $d\sigma/dt_{max}$ is meant to quantitatively express this clinical observation.

2. Methods

2.1. Model geometry development

In this study, the LV is modeled as an ellipsoidal shell that is truncated at its base (Fig. 1). The right ventricle wraps circumferentially around the LV about 180° and extends longitudinally about two-thirds of the distance from the base to the apex. Using such a model, the LV can be defined by the major and minor radii of its two surfaces: the endocardium of the LV, and a surface defined by the epicardium of the free wall and the endocardium of the septum. Streeter and Hanna (1973) described the position of the basal plane using a "truncation factor" f_b, which is defined as the ratio between the longitudinal distances from equator to base ($A/2$) and from equator to apex (A), as illustrated in Fig. 1. The overall longitudinal distance from the base to apex ($=3A/2$) is thus $(1+f_b)$ times the major radius of the ellipse. Because variations in f_b are relatively small between the diastole and systole (0.44–0.5) (Streeter and Hanna, 1973), a constant value of $f_b = 0.5$ is proposed in this study.

From cine-ventriculography, the volumes of myocardial wall and LV are given by

$$\text{MV} = 9\pi[(A+h)(B+h)^2 - AB^2]/8, \quad (1)$$

$$V = 9\pi AB^2/8, \quad (2)$$